USAMP Low-Cost Magnesium Sheet Component Development and Demonstration Project

2020 DOE Merit Review Presentation

Presenter and PI :

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FCA US LLC

United States Automotive Materials Partnership

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Project ID #mat127

Overview

Timeline

- **Start:** October 1, 2016
- **End:** February 28, 2021
- **Percent complete:** ~75% complete

Budget

Total project funding available

- DOE (70%): $5,651,258
- Contractor (30%): $2,421,968

Funding received in FY19

- DOE Share: $1,550,779
- Contractor share: $664,621

Funding planned for FY20

- DOE share: $1,635,873
- Contractor share: $701,088

Partners

Primary recipient – USAMP LLC

Industry subrecipients

- AET Integration, Inc.
- Fuchs Lubricants
- Henkel Corporation
- Quaker Chemical Corporation
- Vehma International of America
- Xtalic Corporation

University subrecipients

- The Ohio State University (OSU)
- University of Florida (UF)
- University of Michigan (UM)
- University of Illinios at Urbana-Champaign (UIUC)
- University of Pennsylvania (UPenn)

LightMAT national laboratory participants

- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

Vendors with substantial technical involvement

- Camanoe Associates
- Inaltech
- POSCO
- FADI-AMT

Barriers

- High cost of Mg sheet material, and challenges in producing automotive components with it, prevents widespread use in automotive applications.
- Lack of adequate predictive tools to enable the low cost manufacturing of lightweight Mg sheet components

Targets

- Overall – 25% vehicle glider mass reduction @ less then $5/lb saved (FOA specific – Mg sheet components at no more than $2.50/lb saved) based on 2017 U.S. DRIVE MTT Roadmap Report

Relevance

Overall objective

- Demonstrate the feasibility of producing Mg sheet components to achieve a component cost increase over conventional steel stamped components of no more than $2.50/lb saved.

Objectives (March 2019 to March 2020)

- Validate Integrated Computational Materials Engineering (ICME) predictions for formability and mechanical properties
- Optimize effective, low cost pretreatments/coatings and lubricants
- Quantify suitable joining processes
- Complete small and medium scale forming evaluations of selected alloy
- Develop material cards for forming analysis

Impact on Barrier(s)

- Mg sheet has the potential to reduce mass of automotive components by up to 65% compared to steel (55% projected for this project) and this project is specifically aimed to address cost and manufacturing challenges preventing widespread use of Mg sheet.
- Demonstrating the feasibility of producing Mg sheet components at the target cost should enable increased usage in automotive applications
- Improved modeling capabilities of Mg alloys from raw ingot through fully formed and painted automotive components will be developed

Approach / Milestones

The program received an 11 month no-cost extension (reflected in the table below) for BP3 due to the following:

- POSCO halted magnesium sheet production in 2019 to restructure its sheet business.
- Additional testing necessary to characterize the texture variation seen in Posco's three unique batches of E-Form Plus (AZXM2110, Mg-2Al-1Zn-0.8Ca-0.3Mn).

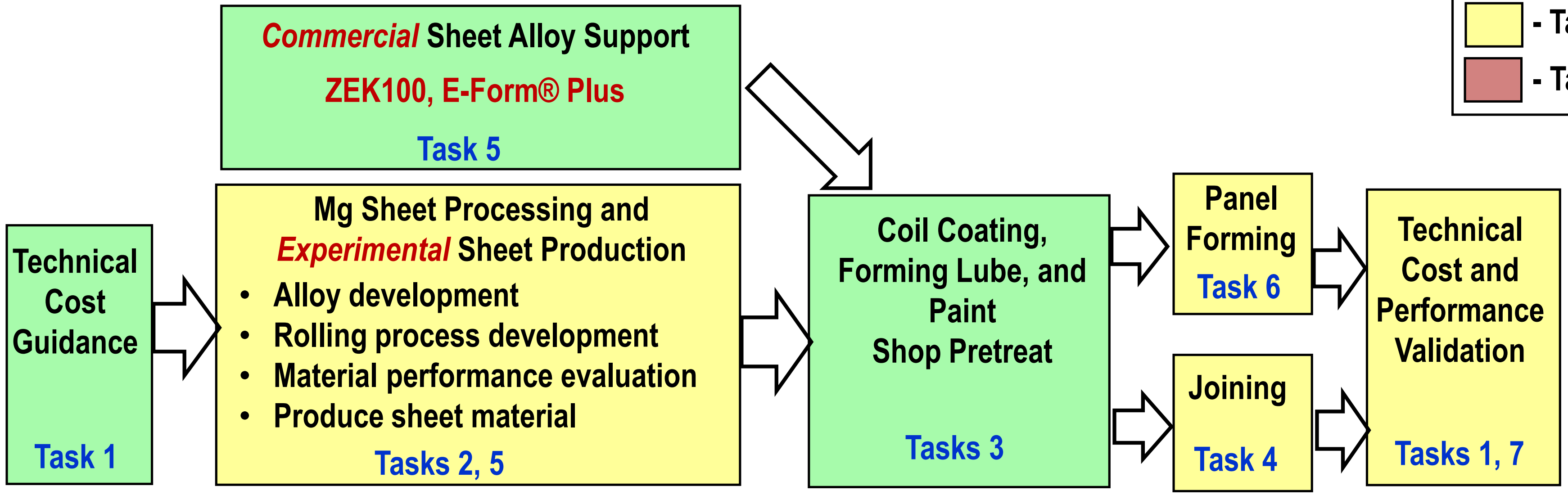
BP	Milestone Number	Milestone Type	Task	Description	Status
1	1	Go/No Go	**Task 0:** Project Management/Contracting	100% of POs issued to subs.	Complete
	2	Technical	**Task 1:** Technical Cost Guidance	Baseline cost model for Mg sheet complete.	Complete
	3	Technical	**Task 2:** Alloy and Sheet Processing Development	New Mg alloy sheet composition(s) identified.	Complete
2	4	Technical	**Task 2:** Alloy and Sheet Processing Development	Constitutive model for textured Mg-alloy completed and ideal texture suggested.	75%*
	5	Technical	**Task 2:** Alloy and Sheet Processing Development	Forming analysis completed on medium sheet.	50%
	6	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Forming lubricant composition identified.	Complete
	7	Go/No Go	**Task 5:** Mg-alloy Sheet Production	Manufacture and deliver experimental medium-width sheets.	Complete
3	8	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Evaluation of corrosion protection coating completed.	90%
	9	Technical	**Task 5:** Mg-alloy Sheet Production	Delivery of wide sheet.	Complete
	10	Technical	**Task 6:** Mg-alloy Large Body Component Production	Mg-alloy panels formed to specifications.	25%
	11	Technical	**Task 7:** Component(s) Demonstration	Final delivery and performance evaluation completed.	50%

Note: * = Milestone is expected to be achieved in BP3 which now concludes on 2/28/2021.

Approach

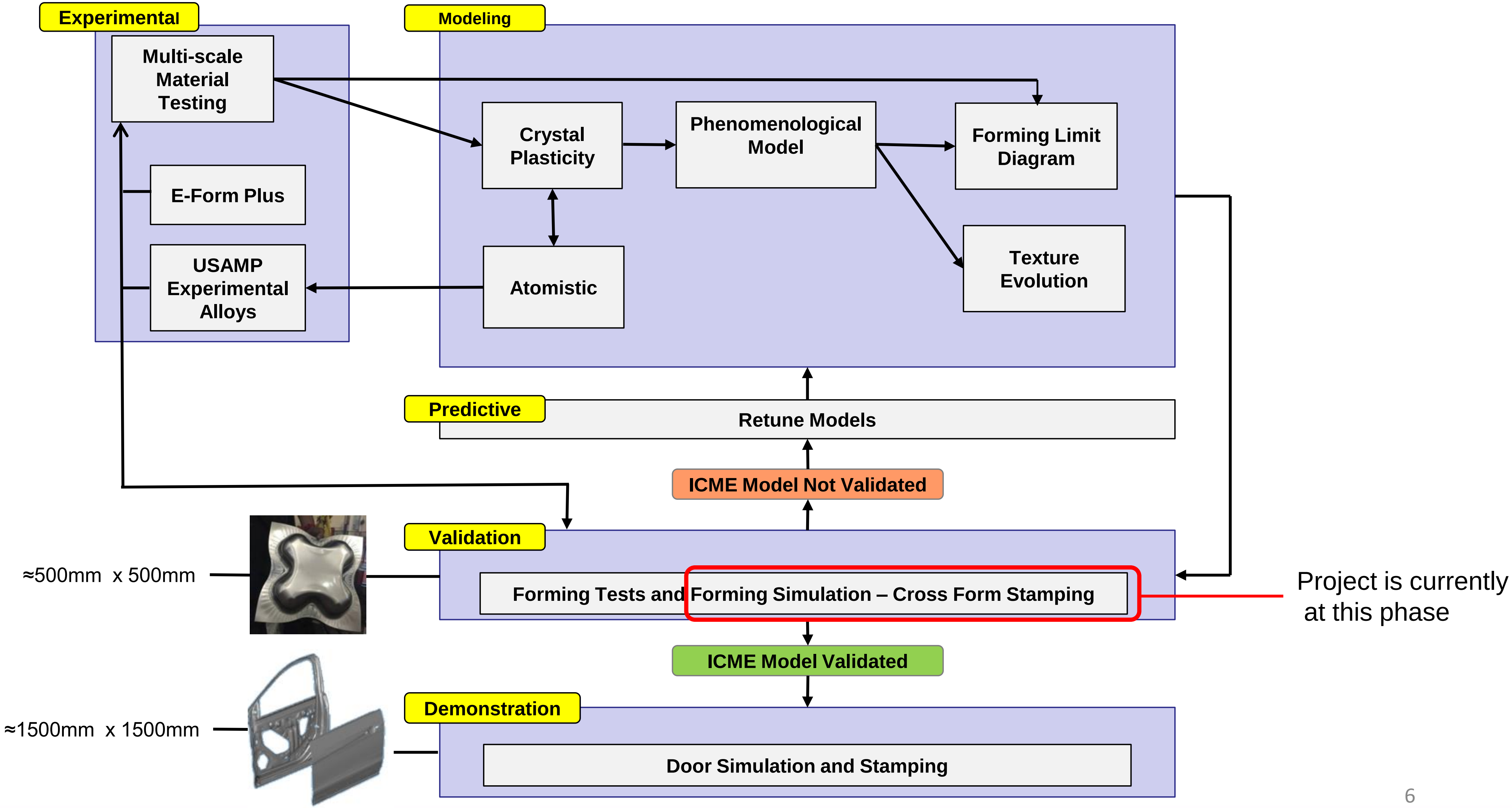
Task 1	Establish a technical cost model to identify Mg cost drivers and verify proposed Mg door components achieve targets.
Task 2	Leverage ICME methods to develop at least one new, low cost Mg alloy suitable for forming large, challenging automotive panels.
Task 3	Develop effective, low cost pretreatments/coatings, forming lubricants and paint shop coatings.
Task 4	Evaluate suitable joining processes.
Task 5	Produce material test samples (both experimental and commercial) to validate ICME predictions for formability and mechanical properties compared to baseline ZEK100 material.
Tasks 6, 7	Produce and evaluate large automotive components.

- Task(s) complete or substantially under way
- Task(s) under way
- Task(s) not started or no substantial progress



Approach

ICME Process and Validation

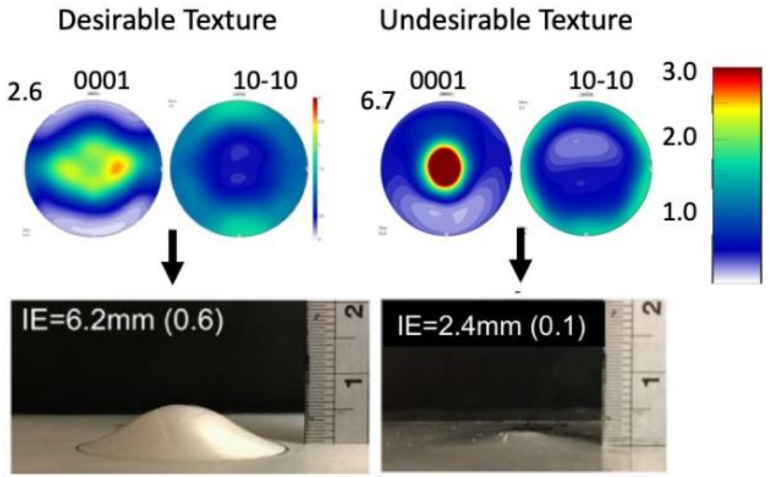


Technical Accomplishments

Previous Accomplishments

Modeling:

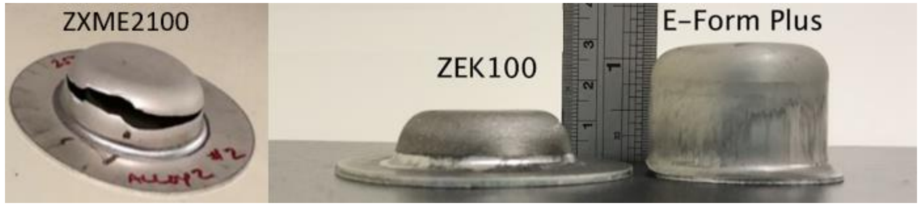
- Identified desirable texture features for enhancing formability
- Fabricated binary and ternary models for microstructure characterization



Left side shows desirable texture and acceptable dome height for E-Form Plus, while and the right side shows Alloy 1 with strong basal texture and poor dome height

Alloy Development:

- Designed Experimental Alloy 2, ZXEM2100 (Mg-2Zn-0.3Ca-0.2Ce-0.4Mn)
- Identified base chemistry for Alloy 3 (Mg-Ca-Zn)
- Performed alloy formability evaluations and <u>**chose E-Form Plus as the final alloy that will be used to form door panels**</u>



Erichsen cup testing of Alloy 2 (left), ZEK100 (center) and E-Form Plus (right) performed at 250°C shows only E-Form plus was capable for forming the full cup without fracture

Coating and Lubricants:

- Evaluated potential coil applied pretreatments, lubricants, and paint shop pretreatment chemistries to work with commercially available E-Form Plus

Technical Accomplishments

ICME Development – Atomistics and Thermodynamics

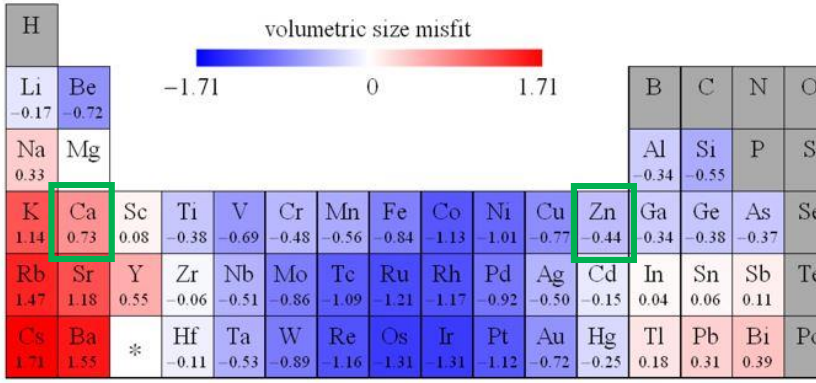
Atomistics/Density Functional Theory (DFT) (UIUC):

- Calculate solution strengthening of non-basal deformation modes to reduce plastic anisotropy (activate more slip systems) for improving ductility

✓ Strengthening potency for $\langle c + a \rangle$ slip and twinning modes scales quadratically with solute size misfit

✓ Scaling enables efficient strengthening predictions for 63 different substitutional solute species

✓ Large solutes show greatest core-solute interactions and are most effective for reducing plastic anisotropy



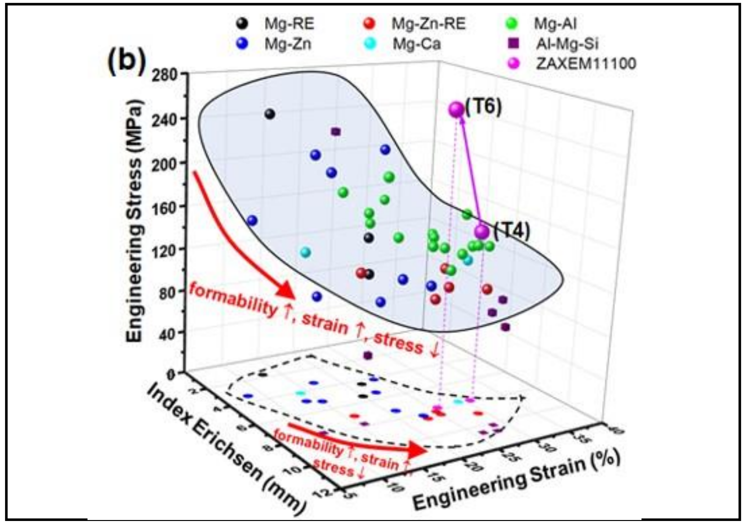
Solute size misfits and solute-induced changes in critical resolved shear stress (CRSS) for 63 substitutional solute species

Computational thermodynamics (OSU):

✓ Designed Alloy 2 **Plus** (ZAXEM11100) based on CALPHAD modeling and optimized multi-stage homogenization and rolling schedules

✓ Alloy 2 Plus achieves outstanding material properties at room temperature

- Elongation (26%)
- Formability (7.7mm Erichsen Index)
- Yield strength (159 MPa at T4)
- Yield strength (270 MPa at T6)



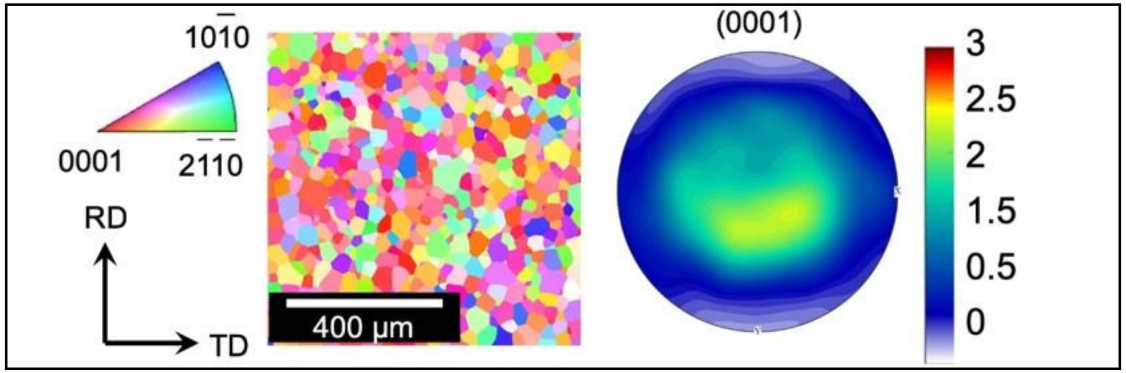
Outstanding formability, ductility and strength of Alloy 2 Plus compared with other Mg alloys

Technical Accomplishments

ICME Development – Texture Development

Alloy effects on texture evolution (UM):

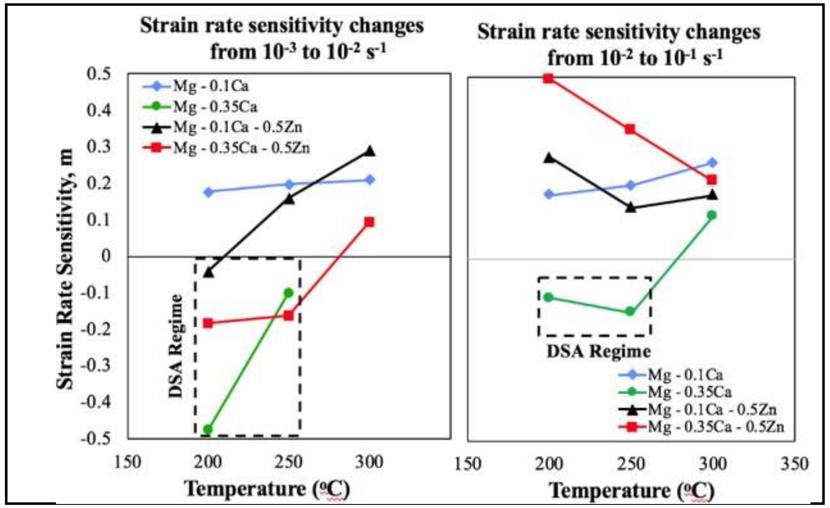
- Optimize alloy chemistry (Alloy 3) and quantify texture evolution mechanisms (deformation vs. recrystallization)
- ✓ Identified promising thermomechanical processing window for Alloy 3
- ✓ Identified desirable texture features for enhancing formability



EBSD inverse pole figure map (left) and basal pole figure (right) of Mg-3Zn-0.1Ca alloy in a specimen subjected to thermomechanical processing that promoted a weak basal texture

Solute effects and texture development (UF):

- Provide input for recrystallization/texture studies
- Develop solute strengthening models
- Validate UIUC DFT calculations
- ✓ Fabricated binary and ternary alloys for different studies (for UM and PNNL/UIUC)
- ✓ Determined Alloy 3 microstructure and conducted Dynamic Strain Aging studies to investigate texture



Identification of strain rate and temperature regime where texture weakening is suspected to occur for 4 alloys

Technical Accomplishments

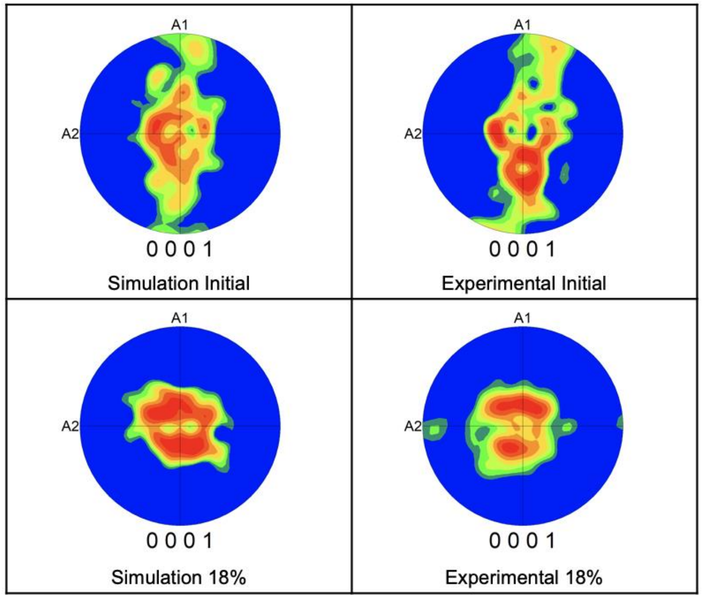
ICME Development – Phenomenological Model

Formability modeling (UPenn and Inaltech):

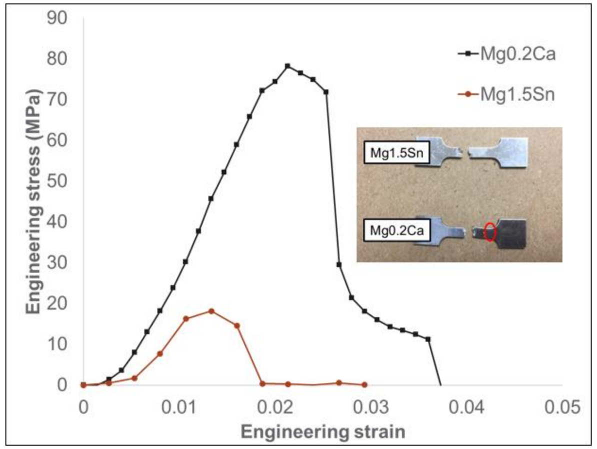
- Develop phenomenological model to predict texture evolution during straining
- ✓ Validated polycrystal model that accounts for evolution of slip and twinning
- ✓ Developed material cards to capture anisotropy and microstructure evolution
- Input from:
    - ✓ EBSD data at interrupted strains (UM, Inaltech)
    - ✓ Array of experiments (PNNL, FADI-AMT)

Inputs for modeling (PNNL):

- Validate UIUC DFT calculations for solute strengthening
- Quantify slip-system-dependent parameters using High Energy X-ray Diffraction (HEXRD) data & Crystal Plasticity modeling of the Mg alloy system
- ✓ Conducted room-temperature, in-situ HEXRD experiments on Mg-0.2Ca and Mg-1.5Sn samples shown in the graph on the lower right (UF)
- ✓ Analyzed lattice elastic strain evolution of as-rolled Mg-Ca and Mg-Sn alloys through in-situ HEXRD



Pole figures predicted from polycrystal model (left) match experimental results (right)



Engineering stress-strain curve for as-rolled Mg-0.2Ca and Mg-1.5Sn show Ca provides higher lattice strain

Technical Accomplishments

ICME and Alloy Development

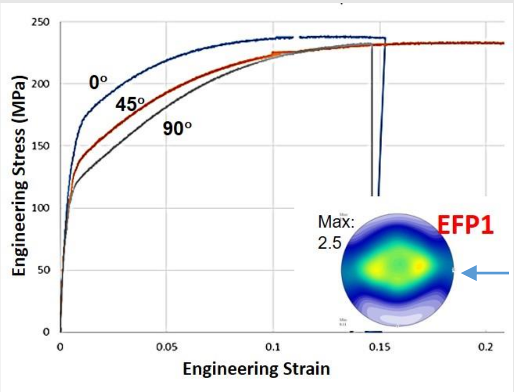
Alloy Number	ICME Inputs	Status
Alloy 1 (ATMZ3100) Mg-3Al-1Sn-0.4Mn-0.3Zn	Thermodynamics and Kinetics	• Phase fractions accurate, BUT • **Appropriate texture (formability) not realized** • **Identified gap between modeled and desired texture**
Alloy 2 (ZXEM2100) Mg-2Zn-0.5Ca-0.2Ce-0.4Mn	+ Atomistics via DFT **(This Project)**	• Great combined strength and elongation • ORNL “shear” rolling mill used • **Formability not realized (still a texture issue)**
Alloy 2 Plus (in progress) (ZAXEM11100) Mg-1Zn-1Al-0.3Ca-0.2Ce-0.4Mn	+ Atomistics via DFT **(This Project)**	• Highest combined strength and elongation ever achieved! • **Room temperature formability improved over alloy 2** • ORNL “shear” rolling mill used as an additional approach to drive improved texture. • Evaluate formability at elevated temperature
Alloy 3 (in progress) Mg-Ca-Zn	+ Recrystallization texture models **(This Project)**	• Chemistry and processing refinement by model improvements and experimental information (This Project) • ORNL “shear” rolling mill to be used

Technical Accomplishments

E-Form Plus Batch Characterization

Room Temperature

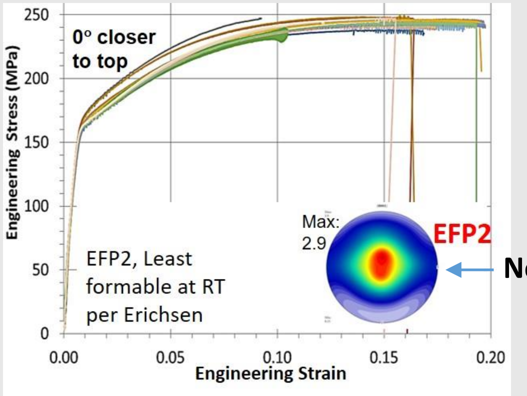
Batch 1 (wide steel mill)



Quad Texture

Batch 1 Stress strain curve and pole figure

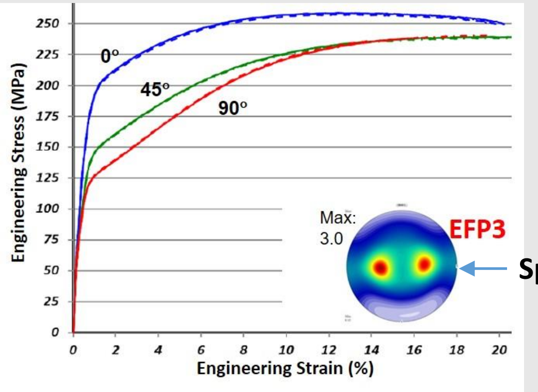
Batch 2 (Pilot mill medium width)



Near Basal

Batch 2 Stress strain curve and pole figure

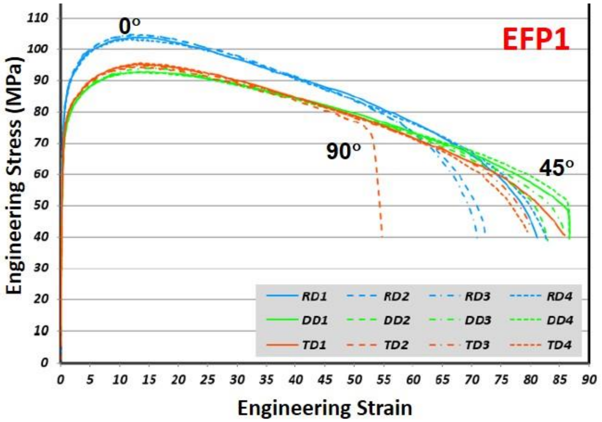
Batch 3 (Wide Aluminum Mill)



Split Peak

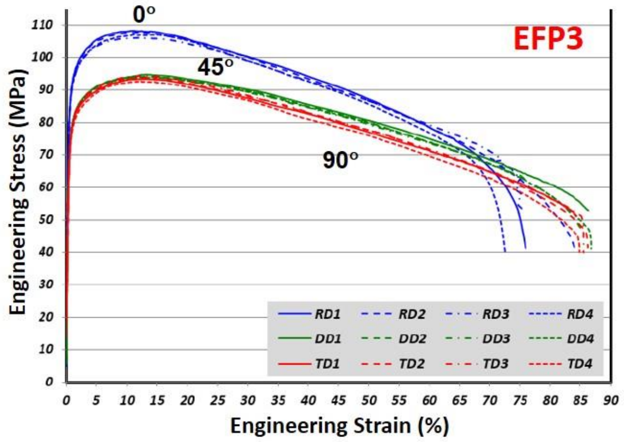
Batch 3 Stress strain curve and pole figure

200°C



Batch 1 Stress strain curve

Not tested at 200°C



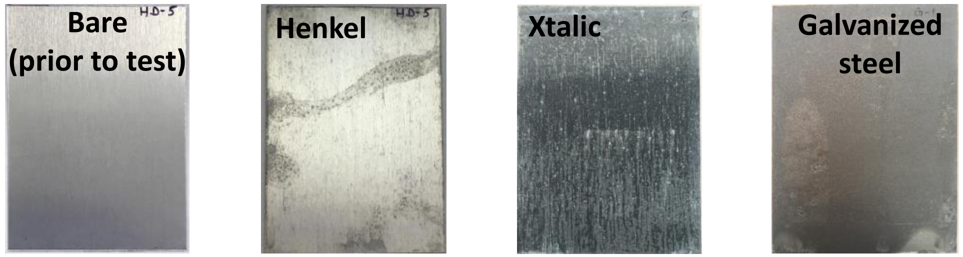
Batch 3 Stress strain curve

- Batch 2 has significantly different texture and tension curves
- Batch 1 and 3 show similar properties at 200°C and will be used for door forming activities

Technical Accomplishments

Coil Applied Coating Development – Henkel and Xtalic

- Henkel optimized pretreatment Process D (conversion coating)
- Xtalic optimized it's zinc coating pretreatment
- Both passed 48 hours ASTM D2247 humidity test

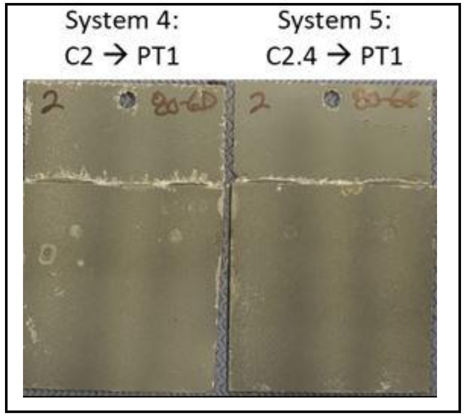


Pretreated Panels of E-Form Plus after 48 hours of humidity testing (ASTM D2247) show Henkel performed better than Xtalic, however both meet specification

Paint Shop Applied Coating Development - PPG

Established effective pretreatment and cleaner systems on multi-metal couples joined with Self Piercing Rivets (SPR)

- ✓ Steel to EFP
- ✓ Aluminum to EFP
- ✓ EFP to EFP



Treated steel and E-Form Plus couples show little corrosion after six weeks of cyclic corrosion testing

Warm Forming Lubricant Development – Fuchs/Quaker

- Practical evaluation of each best performing lubricant
  - ✓ Erichsen deep draw cup design of experiment (DoE)
  - ✓ Cross form stamping DoE
  - ✓ Good parts were achieved at 200°C with both lubricants
- Determined coefficient of friction curves

Fuchs and Quaker lubricants enabled successful cross form stamping at 200°C

Joining Development – AET

Evaluated weld processes on E-Form Plus

- ✓ Identified two electrode types most suitable for resistant spot welding (RSW)
- Preliminary study for laser spot welding had positive results

Electrode Type	Bare			Henkel Pretreat D			Xtalic Zn		
	No Lube	Quaker	Fuchs	No Lube	Quaker	Fuchs	No Lube	Quaker	Fuchs
Ball nose	⇩	N/A	N/A	N/A	N/A	N/A	⇩	N/A	N/A
Truncated	⇩	N/A	N/A	⇩	N/A	N/A	⇩	N/A	N/A
F-type	⇧	⇧	⇧	⇩	N/A	N/A	⇧	tbd	tbd
MRD	⇧	⇧	⇧	⇧	tbd	⇧	⇧	tbd	⇧

⇧ – *Good Weld*
⇩ – *No good*

Spot welding evaluation shows F-type and MRD electrode are most suitable for joining E-Form Plus

Technical Accomplishments

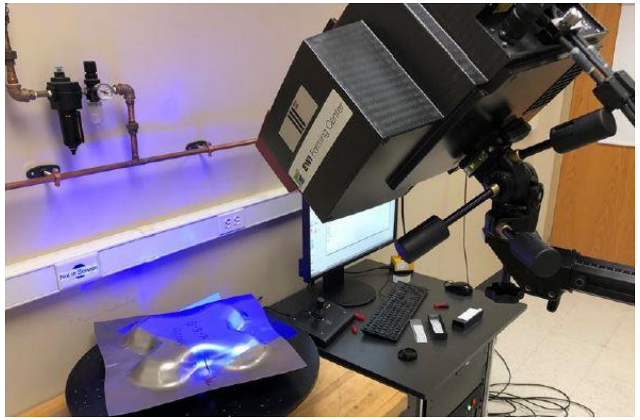
Mg-Alloy Large Body Component Production

Small scale forming of EFP

- Performed Erichsen Cup Test DoE with 60 samples
- Evaluated temperature, lubricant and pretreatment
- ✓ **Identified 200°C as a robust forming temperature**

Medium scale forming of EFP

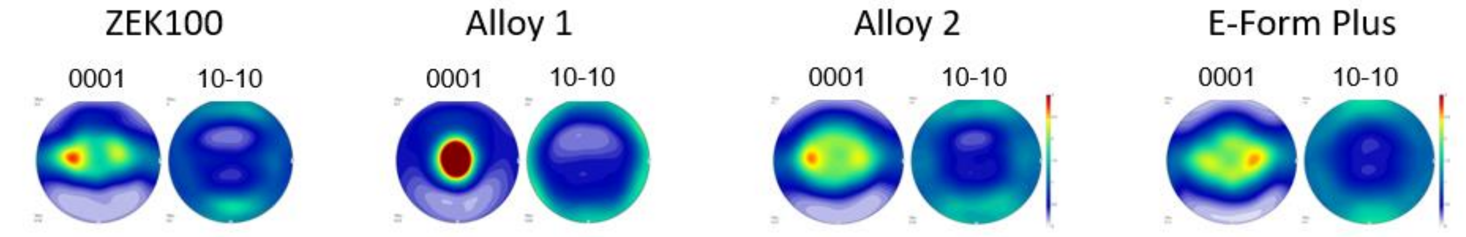
- Performed Cross Form Stamping DoE with 100 samples
- Temperature range of 175°C – 225°C
- ✓ **Successfully formed parts at 200°C with two lubricants**
- Scanned strain map for simulation correlation



Blue light scan of cross form part for correlation with stamping simulation

Successful cross form stamping of E-Form Plus at 200°C

Responses to Previous Years Reviewers' Comments

Comments from the 2019 Annual Merit Review	Response
The total number of alloys that are evaluated, however, are on the lower side. It is possible that more alloys were evaluated but only three were presented.	Only the top 3 alloys were produced and characterized; however, over 30 compositions were initially considered and then narrowed down based on literature studies, CALPHAD analysis, manufacturing limitations, and input from POSCO.
This reviewer stated that an elaboration of the characteristics of the new alloys would be beneficial.	Material characterization included X-ray diffraction, energy dispersive spectroscopy, optical microscopy, scanning electron microscopy, electron backscatter diffraction, In-situ HEXRD tensile testing and quasi-static tension testing. Full material characterization of the new alloys is available and will be included in the final report.  **Pole figures shown for each alloy are just one of the many material characteristics identified in the project**
While the team had tested an existing alloy and chose to continue, the knowledge gained from the work did not contribute to future developments.	The knowledge gained from characterizing E-Form Plus is being integrated into both Alloy 2 plus and Alloy 3. • Batch variation studies on E-Form Plus highlighted the importance of texture as a key enabler for formability in magnesium alloys. • The desired texture will be reproduced on Alloy 2 plus using asymmetric rolling studies. • Verified that Alloy 3 elements Ca and Zn are significant to solid solution strengthening.

Collaboration and Coordination

- Broad participation of domestic OEMs, suppliers and universities (over 15 in total)
- Project executed at task level (7 task teams) and coordinated by a USAMP leadership team

USAMP Leadership Team

Fiat Chrysler Automobiles

Randy Gerken, *Principal Investigator*
Leland Decker
Aslam Adam
Dajun Zhou
Jugraj Singh

Ford

Bita Ghaffari
Mei Li

General Motors

Anil Sachdev
Lou Hector
Arianna Morales

M-Tech International LLC

Manish Mehta, Technical Project Manager
John Carter

Collaboration and Coordination

Organization	Responsibility
Industry subrecipients (7)	
AET Integration, Inc.	- Joining process evaluation
Fuchs Lubricants Co.	- Development of forming lubricants for temperatures up to 250°C
Henkel Corporation	- Development of coil applied anti-corrosion treatments
PPG industries	- Development of paint shop applied anti-corrosion coating for magnesium components
Quaker Chemical Corporation	- Development of forming lubricant for temps up to 250°C
Vehma International of America	- Production (stamping) of large Mg components
Xtalic Corporation	- Develop coil applied aluminum plating for Mg corrosion protection
University subrecipients (5)	
The Ohio State University	- Mg alloy design, evaluation, and validation
University of Florida	- Provide Mg thermodynamic and kinetic data for alloy development
University of Illinois at Urbana-Champaign	- Atomistic modeling for Mg crystal plasticity model development
University of Michigan	- Precipitate evolution and dynamic recrystallization characterization and modeling
University of Pennsylvania	- Develop constitutive model for textured Mg-alloy sheets, FE material user subroutine, drawing and formability simulations, and determine forming limits
LightMAT National laboratory subrecipients (2)	
Oak Ridge National Laboratories (ORNL)	- Development of optimized Mg sheet rolling process parameters and production of Mg strips
Pacific Northwest National Laboratories (PNNL)	- Mg forming model development, data management, and mechanical properties characterization
Vendors (4)	
Camanoe Associates	- Technical cost analysis and guidance
POSCO	- Production of large and medium width Mg sheet
FADI-AMT	- Mechanical properties characterization of Mg sheet
Inaltech, Inc.	- Develop crystal plasticity model, material cards and forming limit diagram for simulation of Mg sheet

Remaining Challenges and Barriers

- ICME modeling must be further developed and integrated into the design of the third experimental alloy to develop a novel alloy composition methodology capable of warm forming door panels.
- Develop test methods to characterize anisotropy in Mg sheet as current standardized tests were determined to be ineffective.
- Paint shop coatings and joining process interactions must be finalized and fully validated on E-Form Plus.
- Door forming simulation must be complete to guide die modifications.
- Door inner and outer panels must be formed to specification from E-Form Plus at 200°C

Door inner panel (left) and door outer panel (center) will be formed with E-Form plus at 200°C

Proposed Future Research

*** Any proposed future work is subject to change based on funding levels ***

- Proposed Future Work – **FY 2020**
  - Validate ICME predictions for formability and mechanical properties
  - Continue to evaluate suitable joining processes by optimizing resistance spot welding and evaluating laser welding on E-Form Plus
  - Update the technical cost model to include final cost of alloy, rolling process, coatings, treatments, lubes, etc. for comparison to current Mg alloys and baseline steel door
  - Perform forming simulation to guide door die modification and compare state-of-the-art material card accuracy with newly developed card incorporating anisotropy, temperature and strain rate dependence.
  - Produce and evaluate the door outer panel

- Proposed Future Work – **FY 2021**
  - Produce and evaluate the door inner panel
  - Create final project reports and close out project.

USAMP

Summary

Project leverages broad industry and academic participation:

- 21 participants doing substantial technical work, including 3 U.S. Auto OEMS, 7 industry subrecipients, 4 vendors, 5 universities, and 2 national laboratories (via LightMAT)

The holistic approach, with the exception of raw ingot production, includes every major step of the process from:

- Alloy chemistry and sheet rolling process development
- New coil applied coatings and warm forming lubricants
- Warm forming and joining process development
- Print shop pretreatment process developed to work with Mg, Al, and steel
- Final cost, weight, and performance evaluation at end of project

Significant technical accomplishments over this period include:

- Developed paint shop corrosion coating systems **(Milestone 8)** effective for E-Form Plus and mixed material joining.
- Developed and calibrated the crystal plasticity model **(Milestone 4)** and used that model to create material cards incorporating evolving anisotropic symmetries neglected in current state of the art simulations.
- Evaluated medium scale formability of E-Form Plus **(Milestones 5, 10)** and successfully stamped cross form parts at 200°C using coating and lubricants developed in this project – warm forming process window has been identified for door inner/outer parts.

Acknowledgement

Acknowledgment: "This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE0007756."

Technical Back-Up Slides

Technical Back Up

ICME Development – Atomistics and Thermodynamics

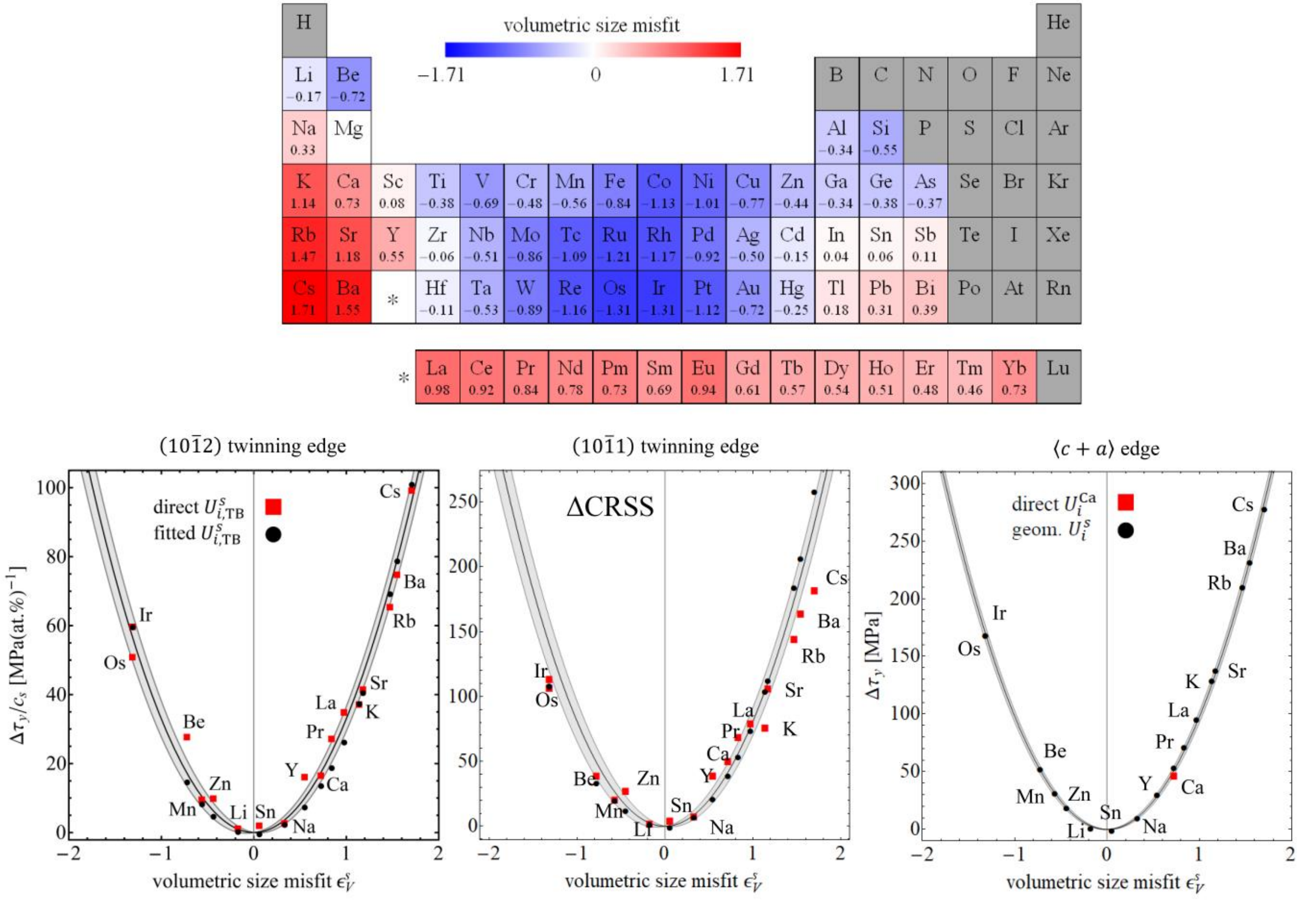
<u>Atomistics/Density Functional Theory (DFT)</u> (UIUC):

- Calculate solution strengthening of non-basal deformation modes to reduce plastic anisotropy (activate more slip systems) for improving ductility

✓ Strengthening potency for $\langle c + a \rangle$ and twinning modes scales quadratically with solute size misfit

✓ Scaling enables efficient strengthening predictions for 63 different substitutional solute species

✓ Large solutes show greatest core-solute interactions and are most effective for reducing plastic anisotropy

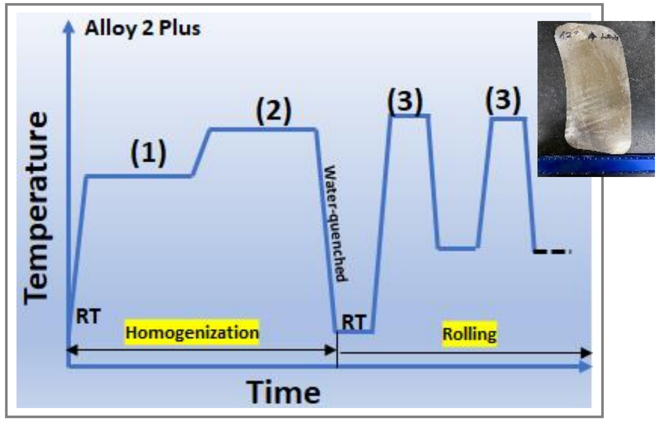


Solute size misfits and solute-induced changes in critical resolved shear stress (CRSS) for 63 substitutional solute species

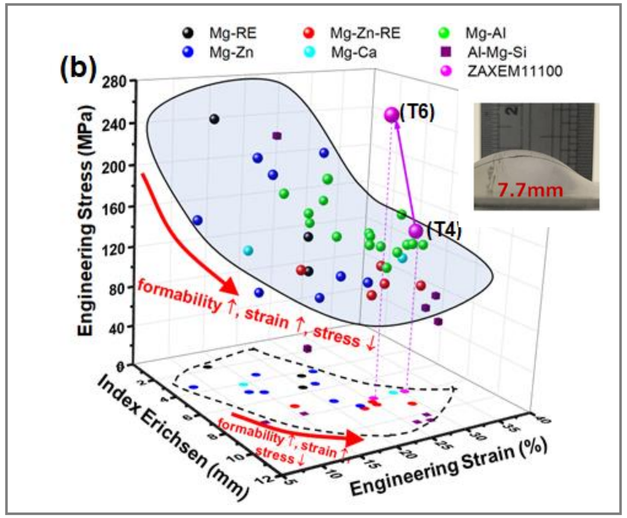
Technical Back Up

ICME Development – Thermodynamic, Kinetics and Alloy Design (OSU)

- ✓ Designed Alloy 2 (Mg-2Zn-0.3Ca-0.2Ce-0.1Mn) and Alloy 2 Plus (Mg-1Zn-1Al-0.3Ca-0.2Ce-0.4Mn) based on CALPHAD modeling and experiments
- ✓ Defined multi-stage homogenization and rolling schedules to maximize use of alloying additions for Alloy 2 and Alloy 2 Plus, based on CALPHAD and kinetics (diffusion) modeling
- ✓ Alloy 2 Plus has no edge-cracking during rolling, and achieved outstanding formability at room temperature: 7.7mm Erichsen Index (tested at UM)
- ✓ Alloy 2 Plus has high ductility (26%) and yield strength (159 MPa at T4, and 270 MPa post-forming with a short age-hardening 1 h at 210°C)
- ✓ Thermomechanical processing of Alloy 2 Plus needs further optimization (collaborating with ORNL) based on CALPHAD and diffusion modeling for room-temperature forming applications



Multi-stage homogenization and rolling schedule for Alloy 2 Plus based on CALPHAD and diffusion modeling



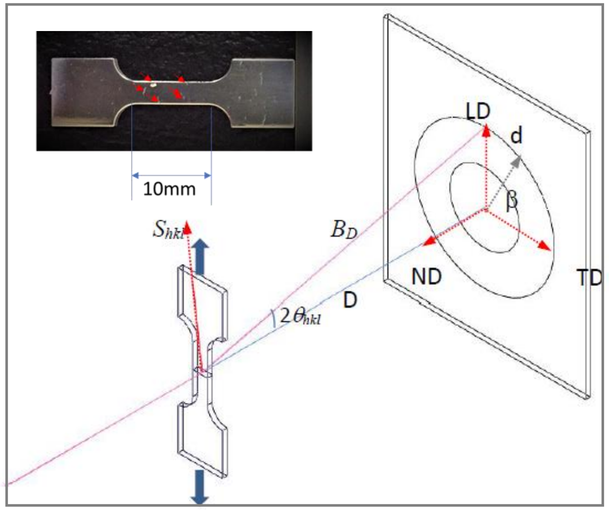
Outstanding formability, ductility and strength of Alloy 2 Plus compared with other experimental Mg alloys

Technical Back Up

Combined in-situ HEXRD experiments and CP modeling to determine constitutive behaviors of Mg Alloys

In-situ HEXRD experiments:

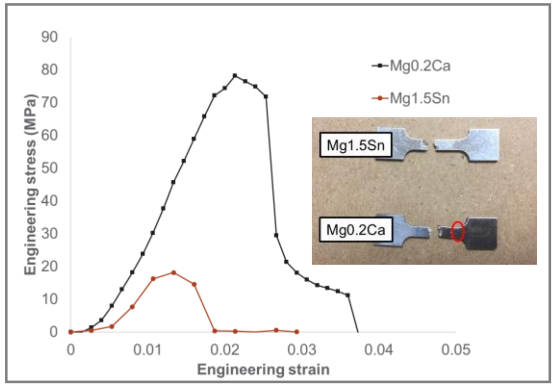
- As-rolled Mg0.2Ca and Mg-1.5Sn were polished for in-situ HEXRD experiments: cracks visible on the surfaces of both samples
- Room temperature tensile tests were carried out at Advanced Photon Source (APS): the Mg-1.5Sn sample failed at very low stress (15 MPa). The Mg-0.2Ca samples shows very low ductility and no work hardening due to the secondary crack
- Using XRD results, lattice elastic strain evolution of as-rolled Mg-Ca and Mg-Sn alloys was analyzed



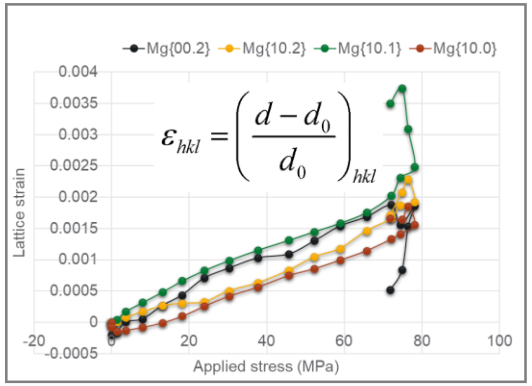
Experimental set-up for In-situ HEXRD and the as-rolled sample with visible cracks on the surface

Plan for next quarter:

- Re-homogenized samples will be used for in-situ HEXRD experiments at next beam time
- Texture measurements (EBSD) post deformation
- Crystal plasticity modeling



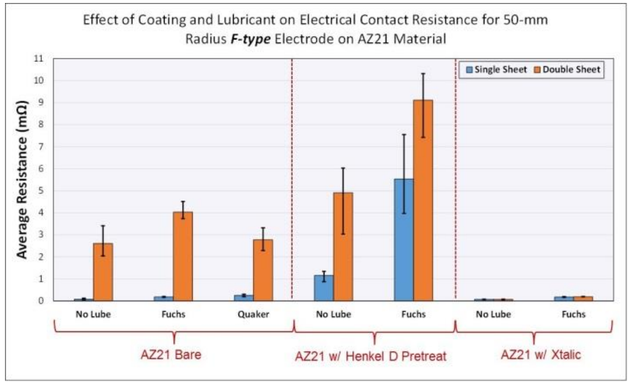
Engineering stress-strain curve for As-rolled Mg-0.2Ca and Mg-1.5Sn

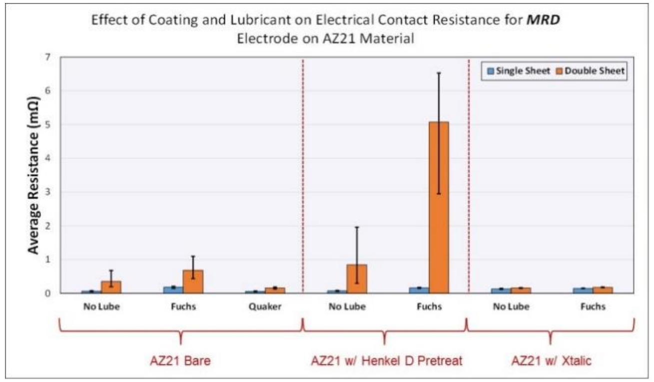


Lattice strain as a function of applied stress of As-rolled Mg-1.5Sn

AET Accomplishments

- Quantified electrical contact resistance and evaluated Resistance Spot Weld (RSW) suitability of four common commercially available Resistance Spot Weld (RSW) electrode types, and down-selected the F-type and Multi Ring Dome (MRD) as being the most promising for additional evaluation with the proposed AZ21 coating/lubricant configurations:
    - ***Bare*** material with no lube, Fuchs, and Quaker lube
    - ***Henkel Process D*** pretreatment with no lube, Fuchs lube, and Quaker lube
    - ***Xtalic Zn*** pretreatment with no lube, Fuchs lube, and Quaker lube





Electrode Type	Bare			Henkel Pretreat D			Xtalic Zn		
	No Lube	Quaker	Fuchs	No Lube	Quaker	Fuchs	No Lube	Quaker	Fuchs
Ball nose	↓	N/A	N/A	N/A	N/A	N/A	↓	N/A	N/A
Truncated	↓	N/A	N/A	↓	N/A	N/A	↓	N/A	N/A
F-type	↑	↑	↑	↓	N/A	N/A	↑	tbd	tbd
MRD	↑	↑	↑	↑	tbd	↑	↑	tbd	↑

↑ – ***Good**** welds have been achieved

↓ – **No** ***good**** welds have been achieved

N/A – No testing planned due to poor results observed in other coating/lubricant configurations

tbd – Insufficient material available at AET

Good* welds – Meet minimum 4√t (4.4 mm) diameter nugget size with no cracks, no expulsion, no interfacial weld failure

- Evaluated initial feasibility of Arplas welding process for bare AZ21
- Evaluated initial feasibility of laser welding process for bare AZ21

Alloys Initially Considered

POSCO strip cast sheet:

TAZ211 (Mg-2Sn-1Al-1Zn-0.4Mn)

For USAMP study:

ZE20 (Mg-2Zn-0.2Ce-0.3Mn)

ZT31 (Mg-2.5Zn-0.5Sn-0.4Mn)

AX52 (Mg-5Al-2Ca-0.4Mn)

AX10 (Mg-0.5Al-0.3Ca-0.4Mn)

TXZ211 (Mg-2Sn-0.5Ca-0.5Zn-0.4Mn)

(Strengthening, Texture and Grain Size)